Fundamental Limitations on Passive Cloaking, and Beyond

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Invisibility has been a powerful cultural theme for millennia. Relevant scientific advances in this fascinating subject have been recently enabled by the field of metamaterials, leading to proof-of-concept demonstrations of actual “invisibility cloaks”. As consistently observed in different studies, however, the ability to hide an object from sight is fundamentally challenging, especially for large objects and broadband illumination (e.g., white light or short pulses).

In our recent work [1], we have analyzed these challenges for arbitrary electromagnetic cloaks. By taking inspiration from analogous problems that arise in microwave systems [2], we have derived quantitative physical bounds for passive cloaks, stemming from general causality and passivity considerations, which reveal the optimal trade-off between object size, visibility reduction and bandwidth. These theoretical limitations hold for any passive cloaking technique aimed at making an object invisible by reducing the total light scattering, and depend only on the properties and size of the object to be concealed. Our findings confirm that broadband invisibility of human-scale objects at optical frequencies is impossible with passive cloaks of arbitrary complexity. Instead, the derived bounds quantitatively show that robust cloaking performance, of technological and industrial relevance, can be obtained for objects with size smaller or comparable to the wavelength, such as radio-frequency antennas or micro- and nano-sensors at optical frequencies.

Recently, we have also envisioned a path forward in the quest to break the derived bounds on invisibility using active systems, which may allow broadband cloaking by drawing energy from an external source [3]. In this context, we have recently proposed an active metasurface cloak based on balanced distributions of loss and gain, forming a so-called *parity-time symmetric* configuration [4]. The passive and active portions of the cloak work in concert to cancel the reflections and shadows of an object. A thin cloak of this kind allows making large objects unidirectionally invisible.

Our findings provide quantitative tools to assess the performance and applicability of cloaking technology, and suggest that active or nonlinear materials and systems may open exciting directions in the century-long quest for invisibility.

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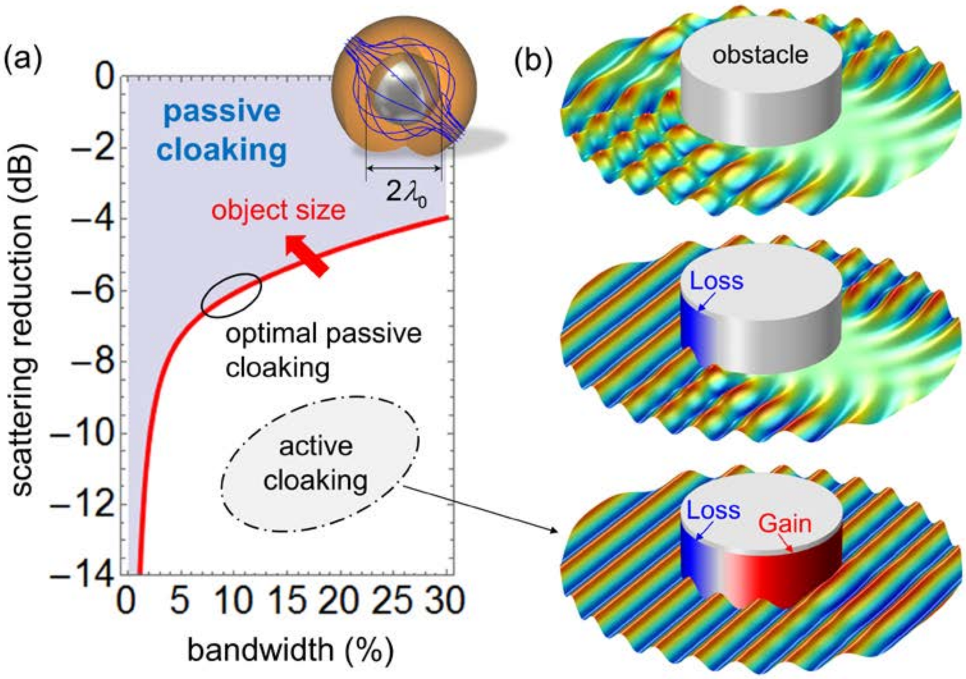

(a) Fundamental trade-off (red line) between how much an object can be made invisible (scattering reduction; vertical axis) and the bandwidth (horizontal axis) over which this effect can be achieved [1]. Here we consider an impenetrable sphere with diameter twice the central wavelength. The trade-off becomes stricter for bigger objects: the red arrow in the figure indicates how the bound changes as the object gets bigger compared to the wavelength. (b) Unidirectional invisibility based on active cloaking [4]. From top to bottom: wave impinging on an impenetrable obstacle; lossy metasurface cloak to suppress reflections; active metasurface cloak with balanced loss/gain distribution. The temporal evolution of the active cloak is shown in the accompanying video (https://www.youtube.com/watch?v=7t1hOnm6Vt0).